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VARIABILITY OF CROP TREE RESPONSE TO FERTILIZATION IN UNSPACED DOUGLAS-FIR STANDS

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VARIABILITY OF CROP TREE RESPONSE TO OPERATIONAL FERTILIZATION IN UNSPACED DOUGLAS-FIR STANDS.

PROJECT SUBMITTED UNDER THE CANADA-BRITISH COLUMBIA FOREST RESOURCE DEVELOPMENT AGREEMENT 1985-1990 FEDERAL DIRECT DELIVERY (FDD) EXTENSION, DEMONSTRATION, RESEARCH AND DEVELOPMENT SUB-PROGRAM

Reid Carter

EXECUTIVE SUMMARY

- Crop tree response of unspaced immature Douglas-fir to operational fertilization was evaluated using stem analysis techniques eight growing seasons after treatment in three stands (Courtenay, Morton and Sayward) on eastern Vancouver Island.
- Evaluation of stem analysis methodology and sample variability found the sample size and methods used to be more than adequate for the purposes of the study.
- Fertilization significantly increased height growth for 3-4 years, although the effect was quite small and variable.
- Fertilization significantly increased annual volume increment for four years on the Courtenay site, three years on the Morton site and two years on the Sayward site. Volume gained through fertilization after eight growing seasons ranged from 1.9 $m^3 ha^{-1}$ (Sayward) to 10.3 m^3 ha^{-1} (Morton).
- Only a small amount of the total variation in annual volume increment could be attributed to fertilization. Moisture availability during the growing season, during June in particular, accounted for up to 76 % of the variation in annual volume increment. Live crown length and pre-treatment volume were able to account for much of the remaining variation in annual volume increment.
- The importance of growing season moisture availability, large live crowns and pre-treatment diameter suggests that espacement practices that increase mean stem diameter, encourage crown development, and reduce competition for moisture may be more effective tools for increasing crop tree volume growth than fertilization of unspaced stands. Taking advantage of likely synergistic effects between thinning and fertilization is suggested to be the best method for enhancing the growth of crop trees.
- Fertilizer efficiency, defined as cubic meters of stem wood produced per kg of nitrogen applied, was quite low when compared to results found in the Shawnigan Lake fertilizer trials (Barclay and Brix 1985). Fertilizer efficiencies ranged from 0.009 (Sayward) to 0.046 (Morton) m^3 kg N^{-1}.
- Simple rate of return on the fertilizer investment eight years after treatment was found to range from -4.9% to 15.1% with fertilization costs of \$150 ha^{-1} and the value of the extra wood estimated to be \$45 m^3.

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INTRODUCTION

A considerable body of knowledge exists concerning the response of Douglas-fir to fertilization with nitrogen sources. Response to fertilization, thinning and the fertilizer-thinning interaction has primarily been examined in established fertilizer trials (Mitchell and Kellogg 1970; Miller and Webster 1979; Miller *et al.* 1979; Strand and DeBell 1979; and Barclay *et al.* 1982, Barclay and Brix 1985, Carter and Scagel 1989). The best of these studies have examined response of individual trees, and response on an areal basis over time. A review of the literature leads one to several conclusions relevant to this study:

1. Response on an areal basis is strongly affected by stand stocking level at time of treatment. If nitrogen is limiting growth, the greatest areal response to treatment will be in stands with a basal area normality of between sixty and ninety percent.

2. Individual tree response to fertilization is greatest in less dense stands where individuals have room to expand their crowns upon stimulation.

3. Mortality rates increase following fertilization in relation to stand density and structure at time of treatment. Mortality rates are highest in dense stands. In general, it is the smaller diameter trees that are affected.

4. Response to operational fertilization is likely to be lower and more variable than that found in research trials (Ballard and Kelliher 1984).

Due to an uneven distribution of volume classes in many coastal Timber Supply Areas, silviculturists are very interested in intensive silvicultural practices which might be used to shorten crop tree rotation length. The primary objective of government and industrial silviculturists targeting a saw-log objective is to gain a response to fertilization on a crop tree, rather than an areal basis. This study will examine whether response of future crop trees in relatively dense, unspaced stands is similar to crop tree response in spaced stands as a result of the usually dominant position of these trees in the canopy. Stand structural and environmental characteristics are examined in relation to crop tree response in an effort to create a picture of the factors controlling crop tree response to fertilization.

This study examines volume growth response on a crop tree basis only. This is due to (1) the inherent variability of growth response among trees within treatments, (2) initial differences in stand structure between treatments, (3) sensitivity of the measurement methods employed, and (4) costs associated with adequate replication. Results cited in this study will reflect the criteria used in selection of crop trees. This study will not examine response in relation to different compartments of the stand stratified by height or diameter; nor will it examine response on an areal basis. The effects of mortality are not considered. Instead, the sampling strategy is aimed at ensuring that within-location replication is adequate to identify the magnitude and variability associated with the response of crop trees to treatment.

The results are not intended to be applicable to all Douglas-fir stands; instead, they will provide an indication of the responsiveness of unspaced stands to fertilization across differing site conditions and provide a tie with results cited from research trials.

OBJECTIVES

To identify the magnitude and variability of crop tree response to fertilization with 225 kg ha^{-1} of nitrogen as urea in unspaced stands of immature coastal Douglas-fir.

This study will identify crop tree (e.g., largest 300 dominants/codominants per hectare) response to operational fertilization after a minimum of eight post-treatment growing seasons. At present, there is little information relating the response of operationally fertilized unspaced stands to the response found in fertilizer trials. This study will provide an opportunity for comparison of operational and research results.

METHODS

Stand Selection

Stands considered for use in this study had to meet the following criteria:

1. they must be fully-stocked, unspaced immature stands of coastal Douglas-fir;

2. they must have been operationally fertilized with 225 kg N ha^{-1} as urea, with at least eight post-treatment growing seasons;

3. unfertilized stands of comparable age, species composition, structure, and site characteristics must be available for use as "control stands"; and,

4. the selected stands should be representative of a range of site and stand conditions found for immature Douglas-fir stands in the Very Dry (CWHxm) and Dry (CWHdm) Coastal Western Hemlock biogeoclimatic subzones (Carter and Klinka 1988).

Three stands were selected from a total of eight candidate stands. Site and stand conditions for each stand are given in Tables 1 and 2. These stands are felt to give a broad representation of the range of site and stand conditions encountered in unspaced Douglas-fir stands in the CWHxm and CWHdm biogeoclimatic subzones (Klinka and Carter 1988). The three stands, labelled "Courtenay", "Morton", and "Sayward", belong to two common site units (associations) within the above subzones -- the *Pseudotsuga-Gaultheria-Kindbergia* and *Tsuga-Rhytidiadelphus-Hylocomium* site units (Klinka and Carter 1988). The Courtenay site has a Moderately Dry actual soil moisture regime (SMR) and Poor soil nutrient regime (SNR) (Klinka *et al.* 1984). The Morton site has a Slightly Dry SMR and Poor to Medium SNR while the Sayward site has a Slightly Dry SMR and Medium SNR.

All three stands were fertilized by helicopter using navigated flight lines at a nominal rate of 225 kg N ha^{-1} as urea (46-0-0). The Courtenay and Sayward sites were treated during the fall of 1979 while the Morton site was treated during the spring of 1981.

The height and diameter distribution of all trees down to a 7.5 cm minimum dbh was evaluated in ten 0.01 ha plots within each treatment per site. The height and diameter distributions for each stand are given in Figures 1 and 2. These distributions were examined to identify the lower limits for both height and diameter for the largest 300 trees per hectare. The upper limits necessary to exclude trees in the top 2.5 percentile for height and diameter were also determined. Thirty trees with heights and diameters within these limits were then randomly selected for felling and sampling giving a total of 30 fertilized and 30 control trees on each of the three sites (180 trees). The height and diameter distributions of the sampled trees are also identified in Figures 1 and 2.

Table 1. Site characteristics of the Courtenay, Morton and Sayward sites.

Study Site	Latitude	Longitude	Elevation (m)	BGCL[1] variant	Actual[2] SMR	Actual SNR	Site[3] Unit
Courtenay	49°46'	125°10'	220	CWHxm	Moderately	Poor	2
Morton	50°06'	125°30'	160	CWHdm	Sl. Dry	Medium	3
Sayward	50°04'	125°28'	175	CWHdm	Sl. Dry	Medium	4

[1] BGCL - Biogeoclimatic variant
[2] Actual SMR and SNR - Actual Soil Moisture Regime and Soil Nutrient Regime
[3] (Klinka et al. 1984)
Site Unit - site association (Klinka and Carter 1988)

Table 2. Site index, stocking, species composition and height and diameter distribution in each study stand at time of sampling (1988).

Study site	Age @bh	Site Index m/50 years[1]	Stems/ha[2] Fd	Hw	Cr	Basal Area[3] Fd	Hw	Cr	dbh (cm) max	min	Height (m) max	min
Courtenay												
Fertilized	31	26	1954	0	33	34.4	0	0.1	28.2	<7.5	22.0	4.9
Unfertilized	31	26	1665	17	102	34.3	0	0.7	31.8	<7.5	21.6	5.2
Morton												
Fertilized	35	31	1139	170	204	49.5	6.8	0.1	36.9	9.4	29.1	7.7
Unfertilized	35	31	1258	204	34	44.0	5.5	4.5	35.9	9.8	28.5	7.5
Sayward												
Fertilized	43	33	440	770	0	34.9	27.1	0	54.3	7.9	32.6	6.9
Unfertilized	43	33	408	902	0	41.2	20.4	0	50.3	7.9	32.0	5.4

[1] Site index is calculated using Bruce's curves as presented in Mitchell and Cameron (1985).
[2] Stems per hectare by species where "Fd" - Douglas-fir, "Hw" - western Hemlock, and "Cr" - western redcedar.
[3] Basal Area (m^3 ha^{-1}).

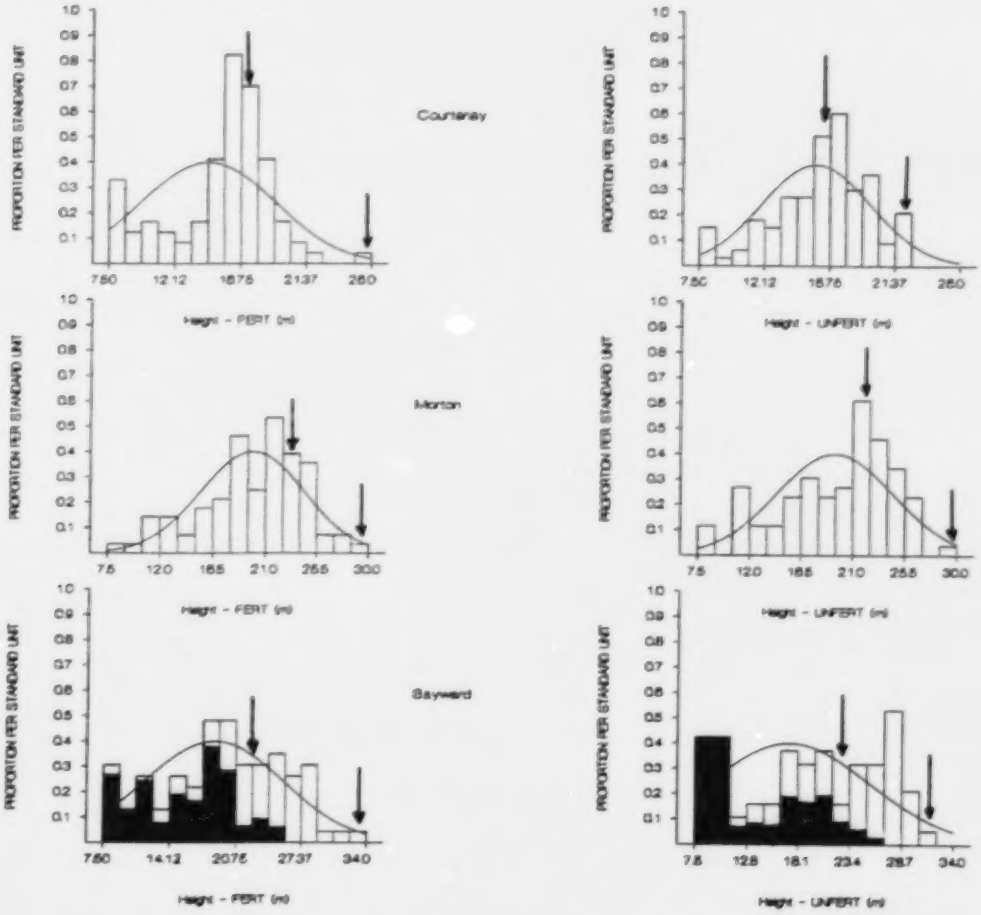

Figure 1. Height distribution of the control and fertilized stands on each site. Trees located between the two arrows are representative of the sampled trees. Shaded portion of the bars on the Sayward site represent western hemlock.

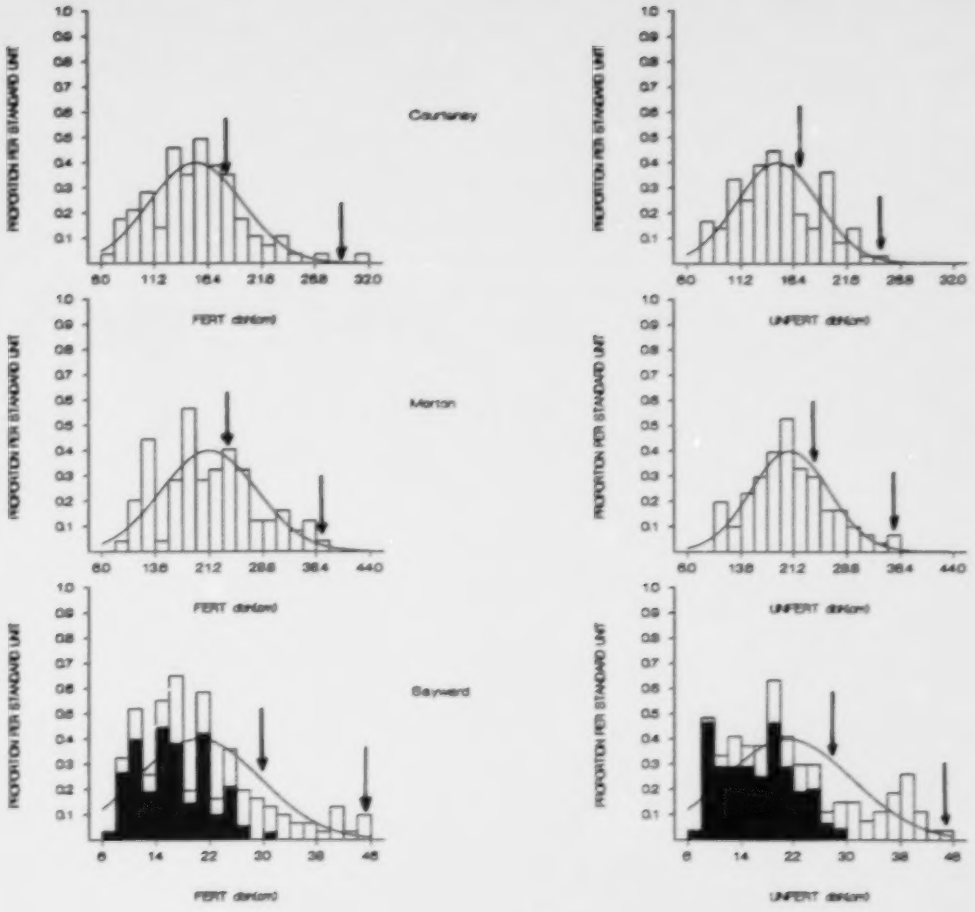

Figure 2. Diameter distribution of the control and fertilized stands on each site. Trees located between the two arrows are representative of the sampled trees. Shaded portion of the bars on the Sayward site represent western hemlock.

Stem Analysis Methods

Field methods

Each sample tree was flagged and numbered prior to felling. Three extra trees were selected in each stand for use as alternative sample trees in cases where sample trees were found to have serious forks or were damaged during felling. All trees were felled and the following measurements were made:

1. total tree height and height to the base of the live crown;

2. length of the longest live branch at the base of the live crown;

3. diameter outside bark at breast height; and,

4. annual height increment for each of the past 15 years.

Cross sectional disks were then taken at stump height (30 cm), 60 cm, breast height (1.3 m) and at eight evenly-spaced intervals along the remainder of the stem to a 7.5 cm top. All disks were labelled on their lower side and shipped to the laboratory for measurement.

Laboratory measurements

Bark thickness, annual increment for each of the past 14 years (1975-1988), and distance to the pith were measured along the longest and shortest radius using an automated digital ring width analyzer (Parker Instruments AGRMM model 3). Measurements were considered accurate to 0.1 mm. All data was transmitted directly from the AGRMM to a microcomputer for editing and analysis.

Volume calculation

Total bark volume, annual volume increment for each year (1975-1987), and the inner core volume (pith to 1974) were calculated using the Tree Ring Analysis Program (TRAP) program of Emanuel and Carter (1986). This program calculated annual volume between each sample height as a linear function, summing the total volume across all sample sections. The quadratic mean radius was used in the area calculation at each sample disk (Husch *et al.* 1982). All volume measurements were based on a 30 cm stump height and a 7.5 cm top diameter.

RESULTS AND DISCUSSION

Sample Size

Sample size was evaluated using the matrix determinant method as outlined in Green (1976) and Emanuel (1984). Ten replicates were used to standardize the sample matrix. Six trees would have been adequate to achieve an alpha < 0.01 with a power of 0.90 in each of the six treatment/site combinations (Dallal 1986). Univariate graphs showing changes in the standard error around the mean from 2 to n-1 samples are given for total volume of each treatment on each site in Appendix 1. The standard error became relatively small and stable for sample sizes greater than 10 to 15 trees on all sites. The sample size of 30 trees/site in this study apparently represents a more than adequate sample size for characterization of volume growth within a site.

Stem Eccentricity

Stem eccentricity, the difference between the longest and shortest radius on each sample disk, was examined to (1) evaluate its effect on volume calculations and (2) identify variation in stem eccentricity relative to stem position. If eccentricity could be shown to have little influence on the accurate measurement of both annual increment and stem radius at a given sample height it might be possible to measure only one radius per disk -- considerably reducing laboratory expenses.

Stem eccentricity was found to have a potentially profound influence on radial increment measurements. The difference between the longest and shortest radii ranged from 17.5 - 24.6% in disks sampled at stump height to an average difference of 11 - 15% throughout the remainder of the stem (Figure 3). Use of the mean radius would have resulted in a significant under-estimation of annual volume calculations. Stem eccentricity declined with increasing height on the stem. This agrees with an earlier study (Carter and Scagel 1989) where it was suggested that optimal sampling height for assessment of radial increment using increment core measurements is likely 2 - 4 m above breast height.

Height Growth

Annual height increment was assessed for each of the past 14 years (1975-1988) and is presented by treatment and site in Table 3 and Figures 4, 5, and 6. Repeated measures analysis of variance and mean contrasts were used to test for significant treatment effects on height growth (Milliken and Johnson 1984). A significant increase in annual height increment occurred as a result of fertilization for the following years on the Courtenay site (1982-1985), Morton site (1981-1983), and the Sayward site during 1982, 1985, and 1988. All differences in annual height increment were significant at $p<0.01$. The percentage of the total variation in height growth explained by the treatment effect for each of the twelve years is presented for each site in Figure 7. The fertilizer effect on the Courtenay site accounted for as much as 59% of the total variation in height growth, whereas this effect accounted for only a small and variable percentage of the total variation in height growth on the Morton and Sayward sites (Figure 7).

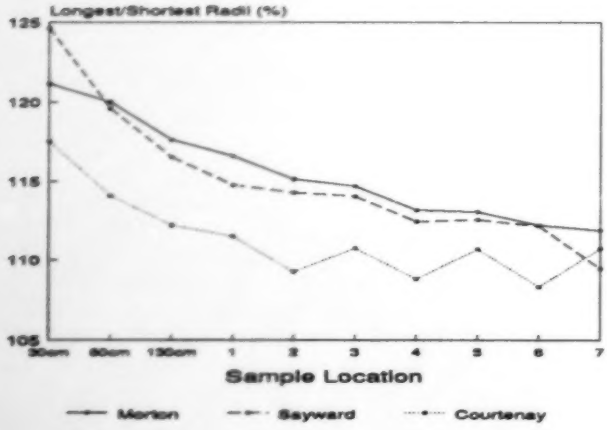

Figure 3. Decline in stem eccentricity with increasing height on each of the three sites.

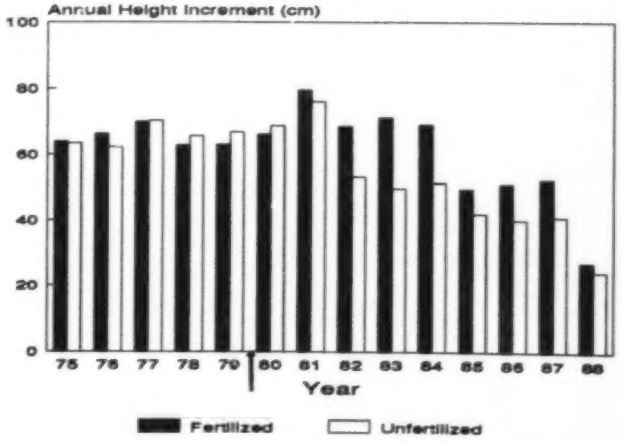

Figure 4. Comparison of pre- and post-treatment annual height increment of the fertilized and control trees on the Courtenay site. (Arrow represents time of fertilization).

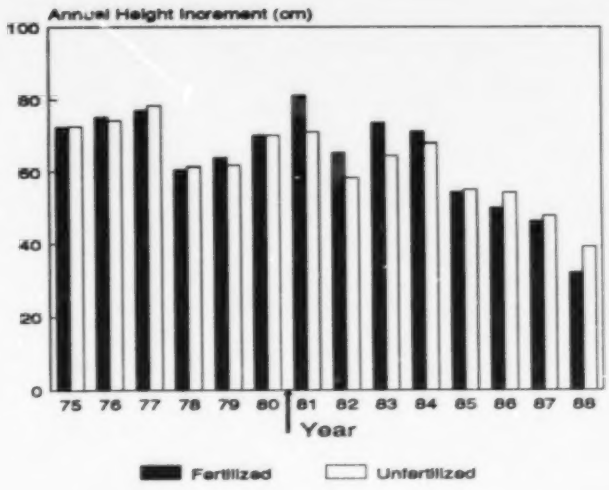

Figure 5. Comparison of pre- and post-treatment annual height increment of the fertilized and control trees on the Morton site. (Arrow represents time of fertilization).

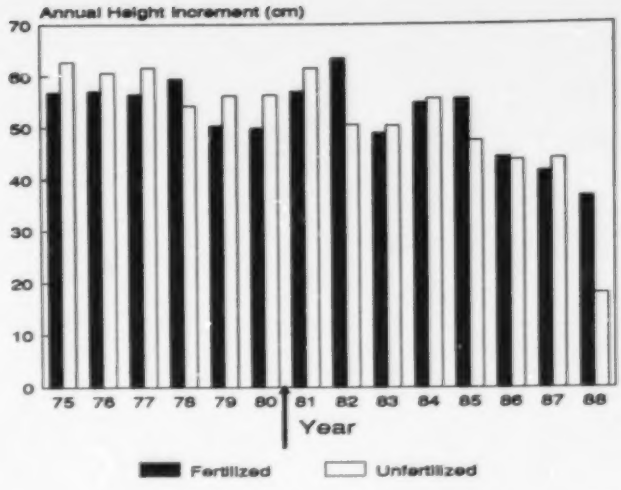

Figure 6. Comparison of pre- and post-treatment annual height increment of the fertilized and control trees on the Sayward site. (Arrow represents time of fertilization).

Table 3. Total height (1988), dbh, bark thickness, length of the live crown (LLC), and length of the longest branch (LLB) for each treatment on each site.[1]

Site Treatment	Height (m)	dbh (cm)	Bark (cm)	LLC (m)	LLB (m)	Annual Height Increment (cm) 1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Courtenay																			
Fertilized	20.3	21.6	1.10	9.6	2.3	64.0	66.2	69.8	62.8	63.0	66.0	79.4	68.4	71.2	69.1	49.3	51.0	52.4	26.9
	1.6	1.8	0.22	1.2	0.2	15.0	13.5	12.4	12.8	14.7	15.1	14.8	6.8	10.3	7.7	12.2	12.0	12.5	5.2
Control	19.4	21.0	1.08	9.0	2.3	63.4	62.2	70.3	65.5	66.7	68.8	76.0	53.3	49.5	51.4	42.0	40.0	40.9	24.2
	1.0	2.0	0.19	0.8	0.3	8.7	10.8	8.5	11.5	10.6	11.5	13.0	12.0	16.4	7.1	8.6	9.0	8.7	8.7
Morton																			
Fertilized	26.0	28.0	1.58	10.6	2.7	72.4	75.1	76.9	60.5	63.8	70.0	81.0	65.3	73.5	71.1	54.4	50.0	46.4	32.0
	1.5	3.1	0.37	1.6	0.4	13.9	10.9	10.1	11.1	9.7	11.5	10.1	12.3	12.6	10.1	11.5	10.3	9.9	8.1
Control	25.1	29.2	1.58	10.2	2.6	72.6	74.2	78.2	61.4	61.9	70.0	70.9	58.4	64.5	67.9	55.0	54.3	47.8	39.2
	1.7	2.6	0.29	1.7	0.4	14.8	11.6	8.8	12.5	11.7	12.7	8.5	9.3	9.6	10.2	10.6	9.9	7.7	9.0
Sayward																			
Fertilized	28.1	37.6	1.99	14.0	3.1	56.8	57.0	56.4	59.4	50.3	49.9	56.9	63.3	48.9	54.7	55.5	44.3	41.5	36.7
	1.9	2.6	0.37	2.5	0.5	9.8	12.2	7.7	12.1	11.2	10.0	12.4	12.4	9.6	13.6	10.5	13.3	8.6	14.3
Control	28.3	36.1	1.84	12.6	3.1	62.7	60.6	61.6	54.2	56.2	56.3	61.5	50.6	50.3	55.5	47.4	43.7	44.0	18.0
	2.2	3.6	0.42	2.7	0.5	10.5	9.6	10.4	11.0	9.5	11.0	15.6	13.4	14.4	10.9	11.6	11.7	14.7	7.4

[1] Upper number is mean; lower number is standard deviation.

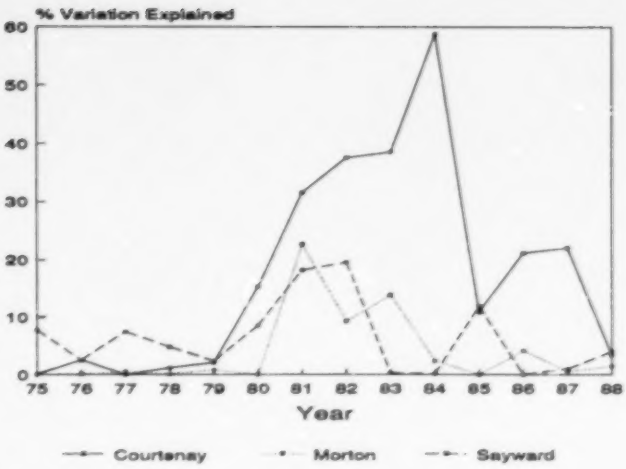

Figure 7. Percentage of total variation in annual height increment explained by the treatment effect on each site.

Volume Increment

Current annual increment

Annual volume increment was adjusted on the Morton and Sayward sites so that pre-treatment volume for both the fertilized and control trees were equivalent (Mitchell and Kellogg 1970). Annual volume of the fertilized trees was increased by a factor of 1.062 on the Morton site and decreased by a factor of 0.963 on the Sayward site. Pre-treatment volume on the Courtenay site was essentially equivalent between treatments and did not require an adjustment. Current annual volume increment of individual trees by treatment and site is presented for each year (1975-1987) in Table 5 and Figure 8, 9, and 10. Current annual increment (CAI) of the largest 300 stems per hectare (CAI_{300}) for the fertilized and control treatments on each site is presented in Table 4.

Table 4. Range in CAI_{300} (m^3) for the fertilized and control trees on each site between 1975 and 1987.

Treatment	Courtenay		Morton		Sayward	
	max	min	max	min	max	min
Fertilized CAI_{300}	6.0	3.2	12.9	7.1	16.6	9.9
Control CAI_{300}	5.1	3.1	10.8	7.1	15.6	10.1

The effect of fertilization on annual increment was examined through the use of repeated measures analysis of variance (Milliken and Johnson 1984). The treatment effect was significant across the 1980-1987 post-treatment sample period for both the Courtenay and Morton sites ($p<0.05$). Mean contrasts were used to identify years with significant treatment effects (Milliken and Johnson 1984, Wilkinson 1988). Fertilization significantly increased annual volume increment for four years on the Courtenay site (1981-1984; $p<0.01$), three years on the Morton site (1981-1983; $p<0.01$), and two years on the Sayward site (1981-1982; $p<0.05$). The F-values from the mean contrasts for the treatment effect (1975-1987) for each site are given in Appendix 2. The F-values for the pre-treatment versus pre-treatment and post-treatment versus post-treatment contrasts are generally low and insignificant as would be expected while F-values for contrasts of the pre- versus post-treatment contrasts are considerably higher.

Two covariates were used to partition the sources of variation in annual volume increment. Total merchantable volume in 1975 (CORE), and length of the live crown in 1988 (LLC). Both of these covariates were significant at $p<0.01$ and accounted for much more of the total variation in annual volume increment than the treatment effect. The percentage of total variation in annual volume increment explained by each of these covariates and the treatment effect is presented graphically for each site in Figures 11, 12, and 13. CORE volume explained between 80% (Courtenay) and 39.5% (Sayward) of the total variation in annual volume increment in 1975. This steadily declined through 1981, the first full post-treatment year, where it dropped considerably. LLC generally explained only a small proportion of the total variation in annual volume increment prior to 1980/81 (0.5 - 18%). The amount of variation explained by LLC increased considerably after 1980 accounting for between 20 and 37% of the total variation in annual volume increment.

The SMR of these sites was classified as Moderately or Slightly Dry which suggests a growing season moisture deficit of 0 - 3.5 months with a ratio of actual to potential evapotranspiration of 0.6 - 1.0 (Klinka *et al.* 1984). The effect of growing season water availability on annual volume increment was examined through the use of multiple regression (Chatterjee and Price 1978). Monthly precipitation records for May, June, July, and August (AES 1988) were used as explanatory variables for prediction of annual volume increment between 1975-1987. May-August precipitation accounted for between 45.7 and 75.9% of the total variation in annual volume increment regardless of fertilizer treatment. June precipitation alone was able to account for much of the variation explained by growing season precipitation. June precipitation is presented as an overlay on annual volume increment in Figures 8, 9, and 10. The regression equations and their associated adjusted multiple R^2 values and standard errors are given in Appendix 3. Monthly precipitation values for the 13 year period are given in Appendix 4.

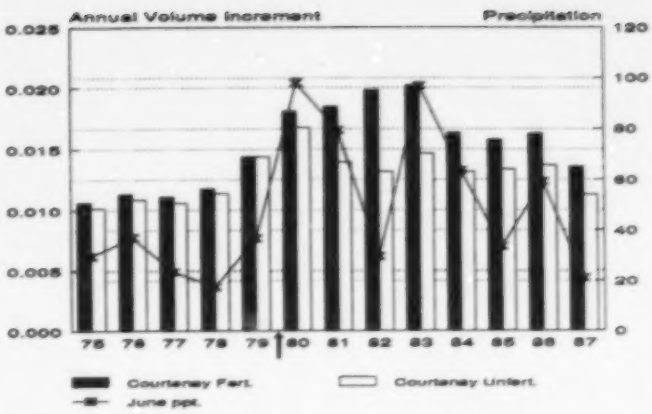

Figure 8. Mean annual volume increment per tree (m^3) for each treatment on the Courtenay site. Line shows total precipitation in June (mm) for each year. (Arrow represents time of fertilization).

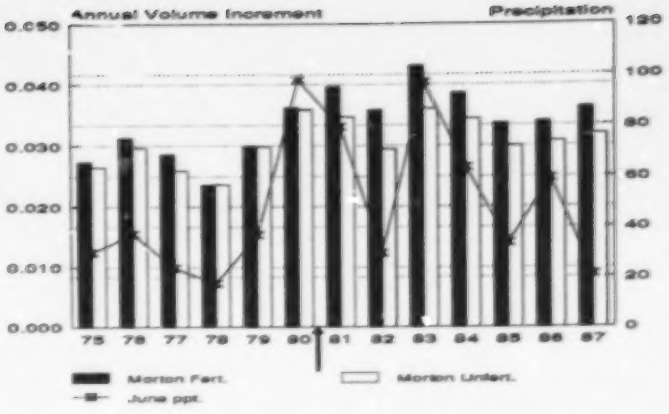

Figure 9. Mean annual volume increment per tree (m^3) for each treatment on the Morton site. Line shows total precipitation in June (mm) for each year. (Arrow represents time of fertilization).

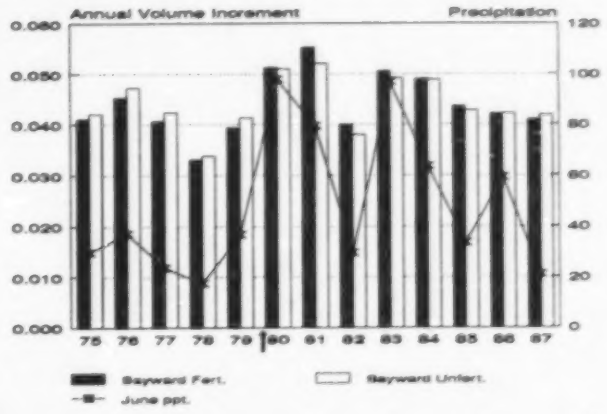

Figure 10. Mean annual volume increment per tree (m^3) for each treatment on the Sayward site. Line shows total precipitation in June (mm) for each year. (Arrow represents time of fertilization).

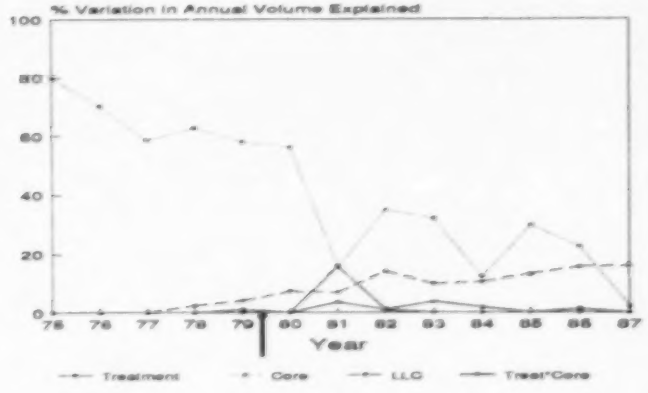

Figure 11. Changes in the amount of total variation in annual volume increment explained by the Treatment, Core, LLC and Treatment*Core interaction effects on the Courtenay site. (Arrow represents time of fertilization).

Table 5. Bark volume, total tree volume in 1974, and annual volume increment (m^3/tree) for each treatment on each site.[1]

Site Treatment	Bark Volume	Total 1974	Annual Volume Increment 1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Courtenay															
Fertilized	0.0532	0.0695	0.0106	0.0113	0.0111	0.0117	0.0144	0.0181	0.0185	0.0198	0.0202	0.0163	0.0157	0.0162	0.0135
	0.0112	0.0194	0.0029	0.0028	0.0025	0.0029	0.0043	0.0050	0.0040	0.0054	0.0043	0.0035	0.0044	0.0044	0.0033
Control	0.0502	0.0720	0.0103	0.0110	0.0107	0.0116	0.0146	0.0169	0.0139	0.0133	0.0147	0.0132	0.0135	0.0138	0.0114
	0.0076	0.0197	0.0027	0.0029	0.0024	0.0033	0.0051	0.0044	0.0023	0.0041	0.0041	0.0031	0.0042	0.0042	0.0024
Morton															
Fertilized	0.1162	0.2312	0.0274	0.0313	0.0286	0.0235	0.0299	0.0362	0.0397	0.0359	0.0431	0.0386	0.0337	0.0339	0.0363
	0.0333	0.0693	0.0079	0.0089	0.0087	0.0072	0.0086	0.0102	0.0121	0.0115	0.0132	0.0121	0.0108	0.0110	0.0117
Control	0.1142	0.2312	0.0265	0.0297	0.0259	0.0236	0.0299	0.0359	0.0347	0.0295	0.0360	0.0345	0.0299	0.0307	0.0319
	0.0249	0.0564	0.0064	0.0076	0.0073	0.0055	0.0069	0.0085	0.0109	0.0079	0.0099	0.0104	0.0087	0.0088	0.0109
Sayward															
Fertilized	0.2006	0.5562	0.0410	0.0453	0.0406	0.0331	0.0394	0.0513	0.0552	0.0398	0.0505	0.0490	0.0436	0.0421	0.0409
	0.0433	0.1152	0.0082	0.0095	0.0080	0.0071	0.0077	0.0099	0.0112	0.0095	0.0101	0.0110	0.0090	0.0098	0.0098
Control	0.1881	0.5562	0.0421	0.0473	0.0423	0.0338	0.0413	0.0510	0.0520	0.0380	0.0492	0.0488	0.0428	0.0422	0.0419
	0.0438	0.1299	0.0086	0.0101	0.0095	0.0075	0.0095	0.0116	0.0129	0.0097	0.0136	0.0134	0.0116	0.0120	0.0123

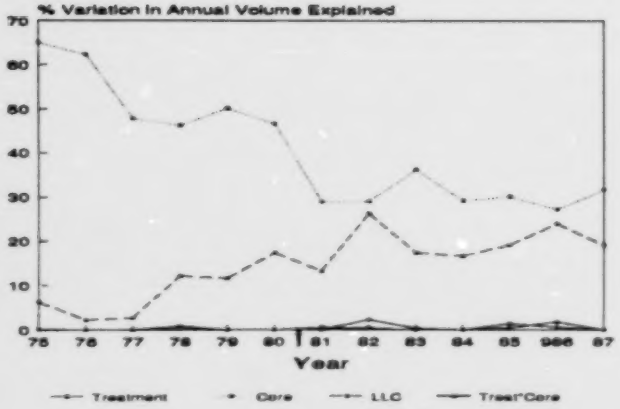

Figure 12. Changes in the amount of total variation in annual volume increment explained by the Treatment, Core, LLC and Treatment*Core Interaction effects on the Morton site. (Arrow represents time of fertilization).

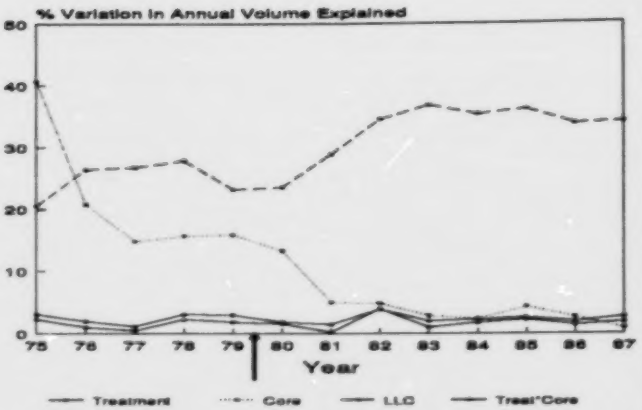

Figure 13. Changes in the amount of total variation in annual volume increment explained by the Treatment, Core, LLC and Treatment*Core Interaction effects on the Sayward site. (Arrow represents time of fertilization).

Although the fertilizer treatment resulted in a significant growth response it only accounted for a very small proportion of the total variation in annual volume increment. Pre-treatment volume, current live crown length, and growing season precipitation were able to account for most of the variation in annual volume increment. These variables had a much larger role in determining individual tree annual volume increment than treatment status on the study sites.

Brix and Mitchell (1986) found soil water potential varied in relation to stand density by as much as 1 MPa during the dry summer months (July-August). This implies that the study stands may have shown a greater response to fertilization if competition for moisture had been reduced through thinning. Silvicultural practices that reduce stand density and maximize the contribution of crop trees to total leaf area might be more effective at promoting annual volume growth of individual trees than fertilization on sites subject to moisture stress. Selection of the largest stems through moderate to heavy, radical low thinnings (Smith 1962) would appear to be a better strategy for promoting volume production than fertilization of unspaced stands. Several studies have shown a positive interaction between fertilization and thinning, suggesting that fertilizer response is likely most reliable in spaced stands (Barclay and Brix 1985; Carter and Scagel 1989).

Cumulative total volume

Cumulative total volume for the largest 300 stems ha^{-1} (CTV_{300}) is presented by treatment and site for the 1975-1987 period in Figures 14-16. The fertilizer treatment on the Courtenay and Morton sites resulted in a distinct increase in CTV_{300} over the 13 year period beginning in 1981. The small, short-term fertilizer-based volume response on the relatively large trees of the

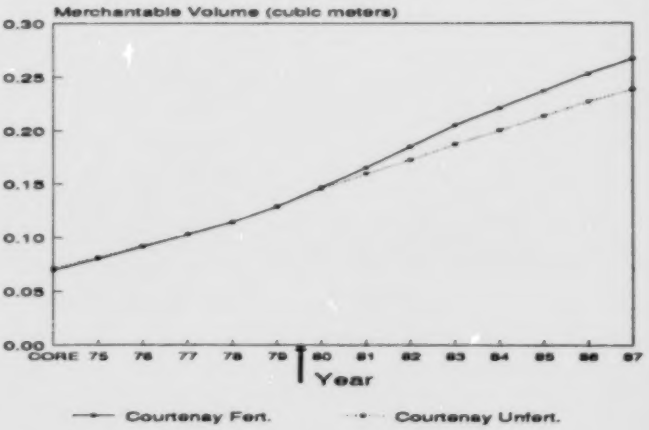

Figure 14. Average cumulative total volume per tree (m^3) for the fertilized and control trees on the Courtenay site. (Arrow represents time of fertilization).

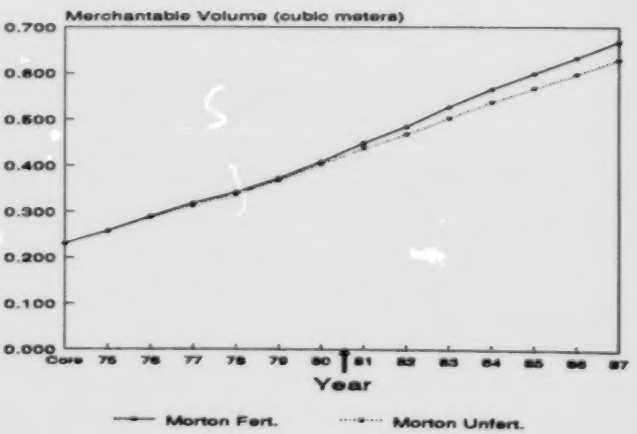

Figure 15. Average cumulative total volume per tree (m^3)for the fertilized and control trees on the Morton site. (Arrow represents time of fertilization)

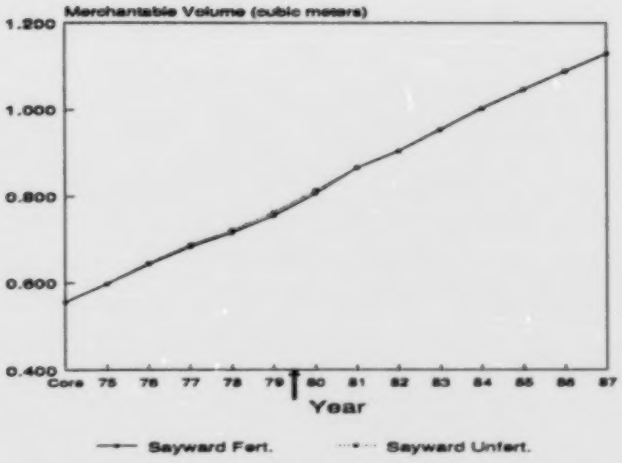

Figure 16. Average cumulative total volume per tree (m^3) for the fertilized and control trees on the Sayward site. (Arrow represents time of fertilization).

Sayward site resulted in a minimal contribution to total volume. The larger responses on the Courtenay and Morton trees resulted in a considerable contribution to total volume appearing even more significant when placed on the relatively smaller trees of these two sites (Figures 14 and 15).

Mean and periodic annual increment

Mean annual increment of the largest 300 stems per hectare (MAI_{300}) was calculated for the control treatment on each site and is presented in Table 6. MAI_{300} is still increasing on all of the study sites and remains well below CAI_{300}. Periodic annual increment for the largest 300 stems per hectare (PAI_{300}) during the post treatment period (1980-1987) is presented by treatment and site in Table 6. The difference in adjusted post-treatment volume between the fertilized and control treatments is assumed to represent net gain due to the fertilizer treatment and is also presented in Table 6.

Table 6. MAI_{300}, PAI_{300}, net gain in merchantable volume, and simple rate of return on investment for each site.

Site/treatment		MAI_{300}[1]	PAI_{300}	Volume[2]	SRI[3]	Merch. $Vol._{300}$
Courtney	Fertilized	na	5.19	8.31	12.1%	74.2
	Control	2.12	4.15	na	na	82.5
Morton	Fertilized	na	11.15	10.3	15.1%	167.3
	Control	4.29	9.86	na	na	177.1
Sayward	Fertilized	na	13.96	1.9	-4.9%	345.6
	Control	7.20	13.72	na	na	247.5

[1]MAI_{300} and PAI_{300} are expressed as cubic meters $year^{-1}$.

[2]Difference in adjusted post-treatment volume between fertilized and control treatment (m^3).

[3]Simple Return on Investment. Assumes a fertilizer application cost to be $150; value of extra wood to be $45/$m^3$, and a carrying period of 8 years.

Diameter Growth

Diameter at breast height, both inside bark (dib) and outside bark (dob), in 1979 and 1987 and change in diameter between 1979 and 1987 (cid) were assessed to determine the comparative sensitivity of simple diameter measurements and stem analysis in measuring treatment responses. Diameters for the fertilized and control treatments were adjusted so that pre-treatment values were equivalent using the same methods used for volume. Pre-treatment diameter was used as a covariate to remove the

effect of differing initial diameters. All diameter measures (e.g., dib, dob, cid) were significantly different between the fertilized and control trees on the Courtenay site ($p<0.01$), while there were no significant differences on the Morton and Sayward sites. The covariate, pre-treatment diameter, was highly significant for all measures and sites; generally accounting for greater than 90% of the total variation in dib, dob, or cid. The fertilizer effect, although significant on the Courtenay site accounted for less than 2% of the total variation in these measures.

It is unlikely that the short-term fertilizer response found on the Morton and Sayward sites would have been identified using diameter measurements alone. Stem analysis methods, although destructive, expensive, and time consuming appear to provide several opportunities not available through periodic diameter measurements. Stem analysis gives reasonably accurate measurements of total or merchantable annual volume increment for both pre-treatment and post-treatment periods. This allows relationships between annual volume increment and time, treatment and environmental factors to be examined with considerable confidence. Non-destructive diameter measurements using fixed dendrometer bands or a diameter tape at a fixed location requires repeated sampling, does not allow assessment of pre-treatment growth patterns, and requires the use of volume equations which introduce additional computational inaccuracy.

Fertilizer Efficiency

The efficiency of nitrogen fertilization, measured as stem volume response (cubic meters) per kilogram of N applied (Barclay and Brix 1985) was calculated for each site. This measure is useful for comparing the fertilizer response between experiments. Fertilizer efficiency for the largest 300 stems per hectare ranged from 0.009 (Sayward) to 0.046 m^3 ha^{-1} kg N^{-1} (Morton). Direct comparisons with fertilizer efficiencies found in other studies are not possible as differences in stand age and density will have a considerable effect on calculated efficiencies. Tree size and age strongly influence volume growth response of individual trees. The largest trees within a given age class will generally show the greatest response. Stand density normally influences response through its effects on crown competition; however, in this study an additional disparity occurs as a result of our use of only 300 stems ha^{-1} rather than all trees. Consequently, fertilizer efficiencies found in this study appear to be quite low. Barclay and Brix (1985) found efficiencies ranging from 0.18 - 0.20 m^3 ha^{-1} kg N^{-1} for a 35 year-old immature Douglas-fir stand on a poor site at Shawnigan Lake, B.C. (site index 21 m/50 years). The stands used in the Shawnigan Lake study had 4175 to 900 stems ha^{-1} compared to the 300 trees ha^{-1} used in this study.

Other explanations for the relatively low fertilizer efficiencies are proposed:

(1) the uniformity of fertilizer applications in small, hand-applied, fixed-area trials such as Shawnigan Lake is normally much greater than found in large operational applications, this may result in a fall-down in fertilizer efficiency in operational treatments;

(2) nitrogen limitations to growth on the sites used in this study may not be as severe as at Shawnigan Lake. The stands used in this study had a higher site index and less visible chlorosis than the Shawnigan Lake stands; and,

(3) some factor(s) other than nitrogen (e.g., competition for moisture and light) may be more limiting than nitrogen on the sites used in this study.

CONCLUSIONS

Stem analysis was an effective tool for identifying trends in annual height, diameter, and volume increment. Thirty trees per stand provided an adequate sample for evaluation of crop tree growth in operationally fertilized, immature Douglas-fir.

Studies evaluating annual increment using increment cores should consider sampling at heights greater than four meters to reduce the effects of stem eccentricity. At least two transects be measured on each cross-sectional disk to minimize the effects of stem eccentricity.

A favourable economic response to operational fertilization can be gained in unspaced, operationally fertilized Douglas-fir stands in the CWHxm and CWHdm subzones. However, volume response is likely to be quite variable and less than values commonly found in research trails on similar sites [i.e., this study -- 0.24 to 1.29 m^3 ha^{-1} $year^{-1}$; Carter and Scagel (1989) and Barclay *et al.* (1982) -- 3 to 6.5 m^3 ha^{-1} $year^{-1}$].

Response duration was also less than commonly cited for coastal Douglas-fir on eastern Vancouver Island (Barclay *et al.* 1982, Carter and Scagel 1989). This may have been due to (1) losses through volatilization at time of application, (2) high rates of nitrogen immobolzation, (3) poor uptake by the trees, (4) competition for moisture and/or light in these densely stocked stands or (5) the possibility that nitrogen was not significantly limiting growth on the study sites. If foliar biomass cannot increase following fertilization as a result of excessive crown competition, increased rates of growth will only continue as long as foliar nitrogen levels are kept

elevated above control levels, often only two to four years in coastal Douglas-fir ecosystems (Carter and Klinka 1988, unpublished manuscript). The relatively short-term growth response found in the stands examined in this study suggests that fertilization should be carried out not more than 10 years before rotation if a favourable economic response is to be obtained.

Stands considered for fertilization should ideally be relatively free of growing season moisture deficits and their nutrient status evaluated prior to treatment. This was supported by the finding that growing season moisture availablity was of greater importance than alleviating nitrogen deficiency through fertilization. Unspaced stands considered for operational fertilization should also have well expressed dominance in a suitable number of crop trees. Live crowns in these future crop trees should be quite large and relatively free of competition from adjacent trees of similar crown class.

The high significance of pre-treatment volume as a covariate with treatment is consistent with other studies (Auchmoody 1986; Carter and Scagel 1989). In immature stands where CAI is still increasing, the larger stems in a stand generally have the highest CAI's. The duration and magnitude of a fertilizer response that increases stem size is normally confounded by this stem size by CAI interaction (Auchmoody 1986). The greatest fertilizer response occurs on the largest trees as a result of this positive interaction. Stands that do not have well established dominants should not be fertilized or should be spaced prior to fertilization.

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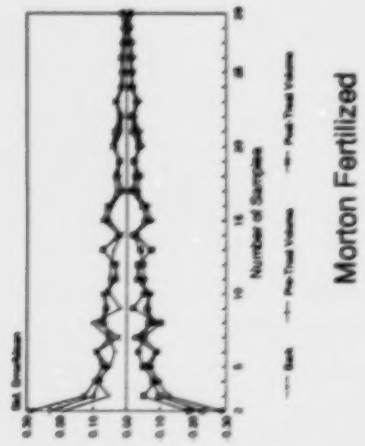
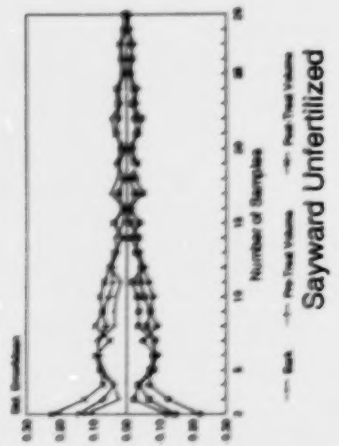
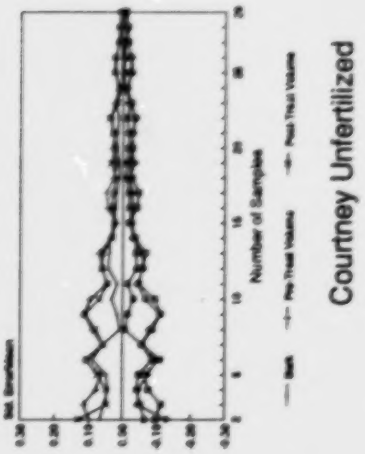
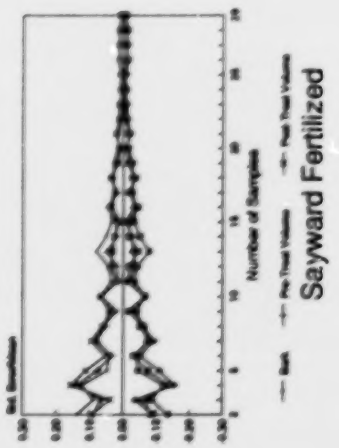
APPENDICES

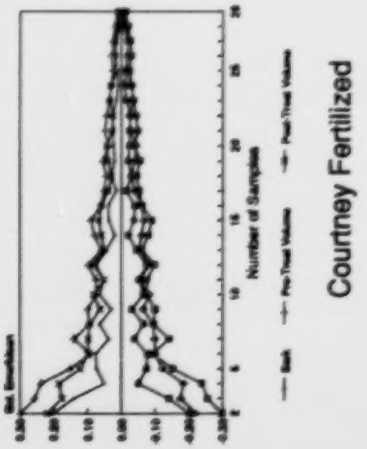
Appendix 1. Effect of increasing sample size on the standard error. The standard error becomes relatively small and stable when sample size is greater than 15 - 17 trees.

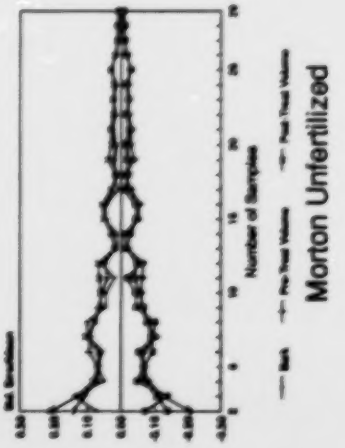












Appendix 2. F-values for mean contrasts of the treatment effect on annual volume increment for each year on each site. F-values are significant at P<0.05 when > 4.01; p<0.01 when > 7.10 (df=1,57).

Courtney

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
1975	0.00												
1976	0.03	0.00											
1977	0.29	0.81	0.00										
1978	1.90	1.90	2.97	0.00									
1979	5.60	5.60	4.80	5.10	0.00								
1980	0.03	0.01	0.15	0.30	12.50	0.00							
1981	29.90	32.20	36.60	34.60	28.20	27.10	0.00						
1982	62.30	60.60	45.80	98.00	162.90	149.00	1.60	0.00					
1983	49.50	55.80	47.20	81.90	87.10	81.00	0.28	2.10	0.00				
1984	11.30	13.60	14.10	16.90	16.60	9.70	6.50	9.40	14.90	0.00			
1985	3.30	3.70	2.30	8.50	20.20	6.60	13.00	104.30	114.90	4.80	0.00		
1986	3.50	4.20	2.80	8.00	16.40	6.20	14.00	59.60	112.60	5.50	0.15	0.00	
1987	4.90	6.00	5.90	8.00	9.00	4.20	16.60	13.60	17.10	3.60	0.71	0.65	0.00

Morton

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
1975	0.00												
1976	0.81	0.00											
1977	2.60	3.60	0.00										
1978	3.20	2.50	4.80	0.00									
1979	3.00	3.50	5.60	0.02	0.00								
1980	1.40	6.00	8.70	0.00	0.01	0.00							
1981	4.10	6.00	3.10	5.80	7.50	13.50	0.00						
1982	30.40	10.90	4.20	50.90	59.00	42.70	0.57	0.00					
1983	14.40	22.20	11.80	16.30	21.80	38.60	3.95	0.16	0.00				
1984	2.80	3.00	0.60	4.40	5.90	10.60	1.55	2.09	20.80	0.00			
1985	3.80	2.70	0.31	6.80	9.40	15.90	1.17	5.21	12.10	0.12	0.00		
1986	2.30	0.91	0.00	5.30	7.70	12.00	2.18	9.07	13.70	0.86	1.80	0.00	
1987	4.00	3.40	0.75	6.20	8.50	13.40	0.47	2.70	9.50	0.03	0.27	1.77	0.00

Sayward

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
1975	0.00												
1976	2.40	0.00											
1977	0.91	0.20	0.00										
1978	0.17	0.23	1.66	0.00									
1979	0.71	0.10	0.00	2.79	0.00								
1980	0.61	4.02	2.73	0.29	5.14	0.00							
1981	3.37	9.56	8.91	2.67	7.36	4.20	0.00						
1982	2.14	4.60	3.60	2.17	7.60	0.85	0.67	0.00					
1983	0.36	2.05	1.60	0.20	2.07	0.00	5.20	0.86	0.00				
1984	0.00	0.48	0.29	0.07	0.29	0.89	12.10	2.93	2.61	0.00			
1985	0.35	2.53	2.17	0.19	2.87	0.02	3.88	1.44	0.02	1.60	0.00		
1986	0.00	0.58	0.38	0.09	0.51	0.92	6.60	3.69	1.25	0.00	1.80	0.00	
1987	0.24	0.02	0.00	0.53	0.00	1.67	11.00	5.09	4.85	0.89	3.19	0.75	0.00

Appendix 3. Regression equations, adjusted multiple R^2, and standard error for the regression of growing season monthly precipitation on annual volume for each site.

Courtney

Volume = 0.0130 - .00002(May[1]) + .00007(June) + .00001(July) -.00002(August)

n=13 Adjusted multiple $R^2 = 0.46$ Standard error = 0.00216 m^3

Morton

Volume = 0.0273 + .00000(May) + .00010(June) + .00004(July) -.00004(August)

n = 13 Adjusted multiple $R^2 = 0.60$ Standard error = 0.00309 m^3

Sayward

Volume = 0.0334 + .00005(May) + .00015(June) + .00002(July) -.00001(August)

n = 13 Adjusted multiple $R^2 = 0.76$ Standard error = 0.00274 m^3

Courtney

Volume = 0.01072 + .00007(June) n = 13 Adjusted multiple $R^2 = 0.40$ Standard error = 0.00227 m^3

Morton

Volume = 0.02594 + .00013(June) n = 13 Adjusted multiple $R^2 = 0.52$ Standard error = 0.00337 m^3

Sayward

Volume = 0.03590 + .00017(June) n = 13 Adjusted multiple $R^2 = 0.69$ Standard error = 0.00311 m^3

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[1]May, June, July, and August represent montly precipitation totals (mm) for the Campbell River Airport (the nearest AES station).

Appendix 4. May to August monthly precipitation (mm) 1975 - 1987 at the Campbell River Airpost (AES 1988).

YEAR	MAY	JUNE	JULY	AUG
1975	87.1	29.7	5.3	109.2
1976	73.2	37.1	30.0	62.5
1977	113.6	23.6	44.8	39.9
1978	45.6	17.5	1.3	106.5
1979	60.8	36.7	40.9	50.8
1980	44.5	97.9	61.1	52.6
1981	126.4	79.4	48.0	32.1
1982	12.1	29.6	62.9	55.0
1983	37.2	96.8	67.3	33.6
1984	140.2	63.6	25.1	72.5
1985	42.2	33.6	0.0	29.7
1986	85.8	59.3	33.6	5.5
1987	55.7	21.0	63.7	12.5